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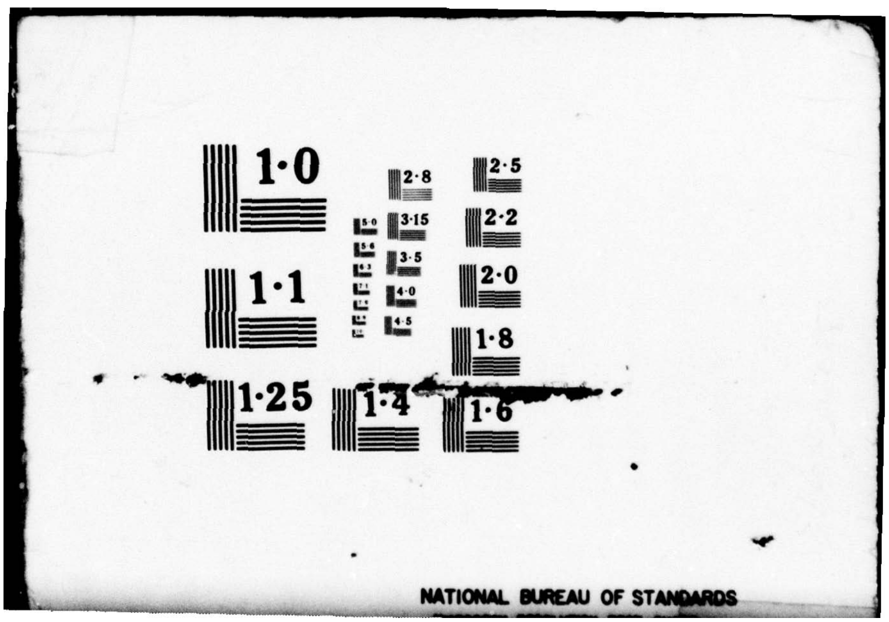
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February 1979

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HUMAN FAILURE DETECTION ATTENTION AND RESOURCE ALLOCATION IN DYNAMIC ENVIRONMENTS

FINAL REPORT

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Christopher D. Wickens

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Prepared for:

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Three major areas of research are summarized. (1) Processing Resource allocation between tasks in dynamic environments. Results indicate that these abilities are distinctly limited. Rather than effectively allocating in response to task demand increases, the operator appears to temporarily "expand" the capability of available processing resources. (2) Failure detection in dynamic systems. Human operators are found to be better at detecting failures (step transitions in the order of a dynamic system) when they are active participants in controlling those systems, than when they are passive monitors of

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the system under autopilot control. Some reasons for this difference are discussed, while research explores the role of training, and information processing channels in the detection process. (3) The attentional demands of failure detection. A model of human processing resources is described which partitions these resources into structure-specific reservoirs related to stages of processing. Task interference patterns between failure detection in the controlling vs. the autopilot monitoring mode, and between two qualitatively different loading tasks are shown to be consistent with this structure-specific resource view.

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Foreword

This Final Report summarizes research accomplished in the period 1 July 1977 to 31 December 1978, sponsored by the Air Force Office of Scientific Research Grant No. 77-3380, originally titled Divided Attention and Task Workload in Control, Failure detection and decision-making in aviation systems. Dr. Alfred R. Fregly, Life Sciences Directorate Air Force Office of Scientific Research was the Program Manager. Professor Christopher D. Wickens, Department of Psychology, University of Illinois was the Principal Investigator.

The early portions of this research were carried out at the Aviation Research Laboratory, Institute of Aviation and represent a continuation of research sponsored by AFOSR Research Contract No. F 44620-76-C-0009 "Human Performance in Aviation Systems," (task 1--Attention, Time-Sharing and Pilot Performance). The majority of the research described in this report was accomplished in the Engineering-Psychology Research Laboratory, an interdisciplinary research facility operated jointly by the Departments of Psychology and Mechanical Engineering, University of Illinois. Special acknowledgement is made to Roger Marsh for his indispensable role in making the new laboratory operational, and for his invaluable assistance in developing and modifying the computer programs used to generate the research reported below.

ABSTRACT

Three major areas of research are summarized. (1) Processing resource allocation between tasks in dynamic environments. Results indicate that these abilities are distinctly limited. Rather than effectively allocating in response to task demand increases, the operator appears to temporarily "expand" the capacity of available processing resources. (2) Failure detection in dynamic systems. Human operators are found to be better at detecting failures (step transitions in the order of a dynamic system) when they are active participants in controlling those systems, than when they are passive monitors of the system under autopilot control. Some reasons for this difference are discussed, while research explores the role of training, and information processing channels in the detection process. (3) The attentional demands of failure detection. A model of human processing resources is described which partitions these resources into structure-specific reservoirs related to stages of processing. Task interference patterns between failure detection in the controlling vs. the autopilot monitoring mode, and between two qualitatively different loading tasks are shown to be consistent with this structure-specific resource view.

BACKGROUND

The environment in which the aircraft pilot operates is a dynamic one. The various control, monitoring and decision-making tasks that are required in the course of fulfilling mission objectives must be performed in the face of environmental conditions, task inputs and system responses that may vary dramatically and unpredictably from one minute to the next. In a comprehensive summary, Young (1969) has dealt extensively with human control performance in such time varying conditions. In his representation of the human operator as an adaptive manual controller Young has distinguished between the human response to sudden step changes in task characteristics typifying "catastrophic" failures (e.g. failure of an engine or autopilot control), and the response to more gradual transient or periodic fluctuations typifying for example changes in icing or turbulence conditions, or temporary demand increases imposed by nearby air traffic. A second contrast that was drawn by Young distinguished between the detection of system changes, and the operator's adaptive response to those changes.

In a program of research carried out at the University of Illinois Aviation Research Laboratory and Engineering-Psychology Laboratory over the past two years, we have investigated two characteristics of decision making and control in dynamic environments that parallel the distinctions drawn by Young. One direction of research has examined manual control performance when task difficulty varies in a slow non-catastrophic manner. Research interest here focussed upon the operator's adaptive response to these changes. We have specifically examined, and attempted to model how the operator dynamically allocates and shifts his attentional resources between tasks when confronted with such difficult variations.

A second line of research has examined the operator's response to discrete step changes in the characteristics of the dynamic system under his control and supervision. Our major goal was to evaluate the ability to detect these "catastrophic" system failures and compare this ability between conditions when the operator was in the control loop as an active participant, and when out of the loop serving in the role of passive monitor. A parallel goal was to examine the effects upon failure detection of concurrent loading tasks.

A common theme that has emerged in the course of both lines of research, and which has provided a framework for much of the theoretical and analytical treatment of the results, has concerned the structure of human processing resources. In this endeavor, an effort has been made to establish the extent to which the interference between tasks can be attributed to parameters of task difficulty or to task structure. Results from current studies in conjunction with parallel research efforts in other laboratories have been used to provide the basis for a hybrid theory of task interference that is a mixture of structural theories (e.g., Kerr, 1973; Keele, 1973) and capacity theories (e.g., Moray, 1967; Kahneman, 1973). These three areas of research are summarized in greater detail below.

Resource Allocation in Dynamic Environments

(C. Wickens, B. Pierce and P. Tsang).

The specific research question asked in this area concerns the operator's ability to maintain performance on a task of high priority (a primary task) at a constant level despite fluctuations that occur in that task's level of difficulty. Wickens and Pierce (1978) proposed that when the high priority task was performed concurrently with a task of lesser priority, a policy of optimal attention allocation would dictate that processing resources are borrowed from lower priority activities as primary task difficulty increases, and are returned during intervals of diminished primary task demand. This allocation was proposed to procede in a closed loop fashion as the operator continuously monitors task difficulty and performance levels in order to achieve the desired performance goals. As a consequence of this closed loop behavior, the optimal allocator should demonstrate a relatively high correlation over time between primary task difficulty and secondary task performance (the latter reflecting the varying supply of available resources); correspondingly a relatively low correlation should be observed between primary task difficulty and primary task performance, assuming that task priority instructions are effectively carried out.

Other allocation policies can be predicted as well. If the available resources can be temporarily expanded in the face of increasing primary task demands so as to preserve its performance level without disrupting the secondary task, then a low correlation would be observed between difficulty and performance on both tasks. We label this policy optimal expansion.

Finally, if the operator cannot or does not reallocate resources at all, and his capacity is fixed, then the correlation with difficulty will be high with the primary task, and low with the secondary.

Wickens and Pierce proposed that these forms of allocation behavior can be quantified by computing the linear coherence spectrum [$\rho^2(F)$] relating the time-varying primary task difficulty parameter to a smoothed measure of performance on both tasks. When the variance over time of one measure is reflected in variance of the other, ρ^2 is high (near 1.0). If it is not, ρ^2 is low. The three categories of allocation policy generate different predicted levels of the coherence measure between difficulty and the primary and secondary task performance measures. The predicted coherence values for the three policies are represented schematically in figure 1.

In an initial effort to assess the feasibility of describing the allocation policy by the coherence measure, and establish what that policy might be, Wickens and Pierce (1978) required subjects to perform two concurrent tracking tasks as the difficulty of the task designated as primary was varied in a series of steep ramps and spikes. Difficulty was operationally defined by the order of the tracking control, which could be adjusted to any level on the continuum from first (pure velocity control) to second (pure acceleration control). The difficulty parameter was thus the proportion of acceleration constant (α), ranging in value from 0.0 to 1.0. Eight subjects performed for four days in conditions of variable primary task difficulty and conditions in which the difficulty of the primary task was held constant at an average value of 0.5. Secondary task difficulty was always held constant at $\alpha = 0.5$. Tracking RMS error was calculated for both tasks by computing its average value within a 2 second sliding window calculated every second for the duration of each 2-1/2 minute trial.

The ensemble average of the difficulty and performance data is shown in figure 2 and suggests that the subjects' location behavior, in response to the difficulty function used here, can best be described as a compromise between optimal and non-optimal allocation. That is, performance on both tasks rose and fell with the difficulty fluctuation in the primary task. Substantiating the visual trends evident in figure 2, the coherence analysis revealed that linear coherence was relatively high for both the primary and secondary tasks at the frequencies of variation in primary task demand (ρ^2primary = .95, ρ^2 secondary = .86.

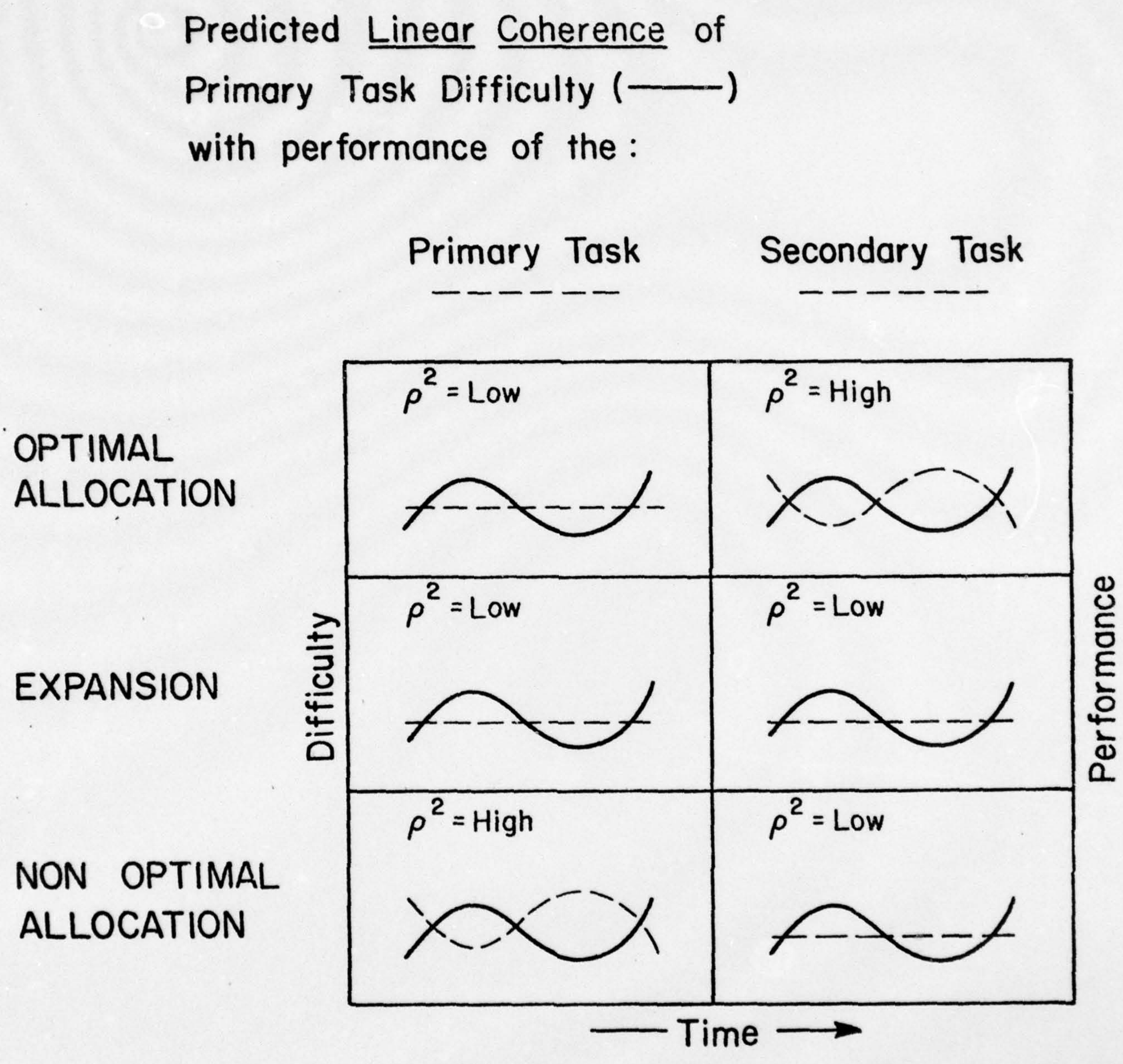

Figure 1. Linear coherence predictions of different allocation models.

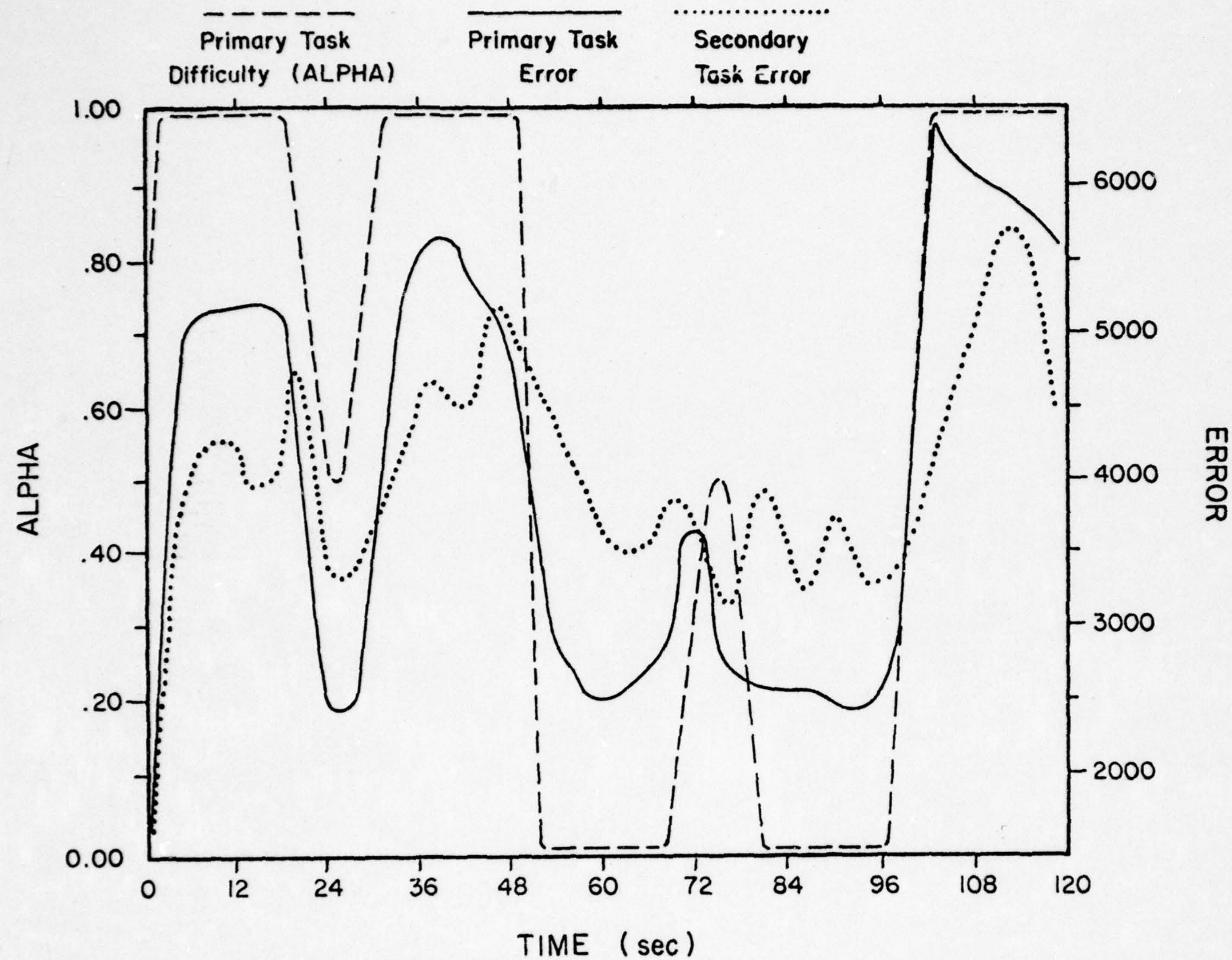

Figure 2: Response of primary and secondary task performance to difficulty variations (Wickens and Pierce, 1978).

A second manipulation in this experiment involved the presentation, on alternate trials of an on-line performance feedback display. Using the bargraph technique developed by North and Gopher (1976), the display presented a continuously updated running average of performance on the primary task which subjects could compare against a representation of the desired criterion level of primary task performance. It was hypothesized that this display might facilitate more optimal allocation by providing subjects with immediate indications of departures from optimum (primary task performance falling below the criterion). Contrary to predictions, however, the presence of the feedback display produced little improvement in the overall degree of optimality and suggested that the major limitation observed in figure 2 lay in the reallocation of resources rather than in the subject's ability to evaluate their performance.

The results of this investigation were somewhat surprising. It was not anticipated that subjects would have as difficult a time following the optimal allocation instructions and maintaining the primary task at a constant performance level. This inability seemed to be somewhat at odds with the conceptualization of attention as a processing resource that can be freely allocated in response to shifting task demands as Kahneman (1973) has proposed.

One of the reasons hypothesized for the limitation in allocation observed by Wickens and Pierce related to the severity or abruptness of the changes in difficulty. It is possible that the difficulty variations employed, and shown in figure 2, were simply beyond the "frequency response" of the operator's resource allocation system. To determine whether this was in fact the case, a second investigation by Wickens and Tsang employed a similar paradigm, with the same frequencies and amplitudes of difficulty variations (proportion acceleration). In an important alteration, however, these frequencies were generated from smooth linear sinusoidal functions of .01, .02, and .03 Hz, rather than the sharp spikes and ramps used in the previous study. Different combinations of these frequencies (.01 and .03 Hz vs. .02 and .03 Hz) were also employed on alternate trials to reduce the possibility that subjects could learn to anticipate the time-course of demand variations. In addition, a larger number of constant difficulty dual task trials were employed in which the difficulty of the primary task (percentage second order component) was maintained during the trial at constant values of 0.0, 0.5, and 1.0.

The results of this study demonstrated only partial agreement with those of the earlier investigation. One important difference related to practice effects. While the non-optimal allocation behavior shown by the subjects in the Wickens and Pierce study did not appear to change over the course of four days of training, the eight subjects employed by Wickens and Tsang showed substantial improvement in allocation behavior over the four days. These practice effects are demonstrated by comparing performance on the first and fourth days of training, portrayed in figure 3, an analogous representation to that depicted in figure 2. It is evident that on day 1, the response is best approximated by the non-optimal allocation strategy shown in figure 1: the response of the primary task to the fluctuation in its own difficulty is clearly visible. While the secondary task also shows considerable time-fluctuations in its performance level, these do not appear to be tightly coupled with the primary task demand changes as might be expected if subjects were appropriately diverting resources from the secondary task. Validating the visual trends in figure 3, the linear coherence measure, averaged across the two frequencies of difficulty variation was equal to 0.58 for the primary task, and only 0.36 for the secondary.

In the lower panel of figure 3, however, it is evident that a change in allocation behavior developed as a result of three further days of practice: the range of fluctuation in primary task error with difficulty appears to be considerably attenuated from day 1, an observation that is substantiated by the reduction in primary task coherence to an average value of 0.50. Thus while still non-optimal, performance is apparently progressing toward optimality. Examination of secondary task performance suggests that the manner in which optimality was being approached was not through an increased ability to reallocate (figure 1, top); secondary task performance is no more sensitive to primary task demands than it was at the outset, a fact reinforced by the low secondary task coherence value of 0.20. Of the models presented in figure 1, it is apparent that the practice trend is toward the behavior typified by optimal expansion. Subjects can seemingly mobilize resources on a temporary basis to handle the increase in primary task demand without sacrificing performance on the secondary task.

Before concluding that the trend with practice is toward optimal expansion however, it was necessary to consider the implementation of another possible strategy, that could generate a similar pattern of coherence

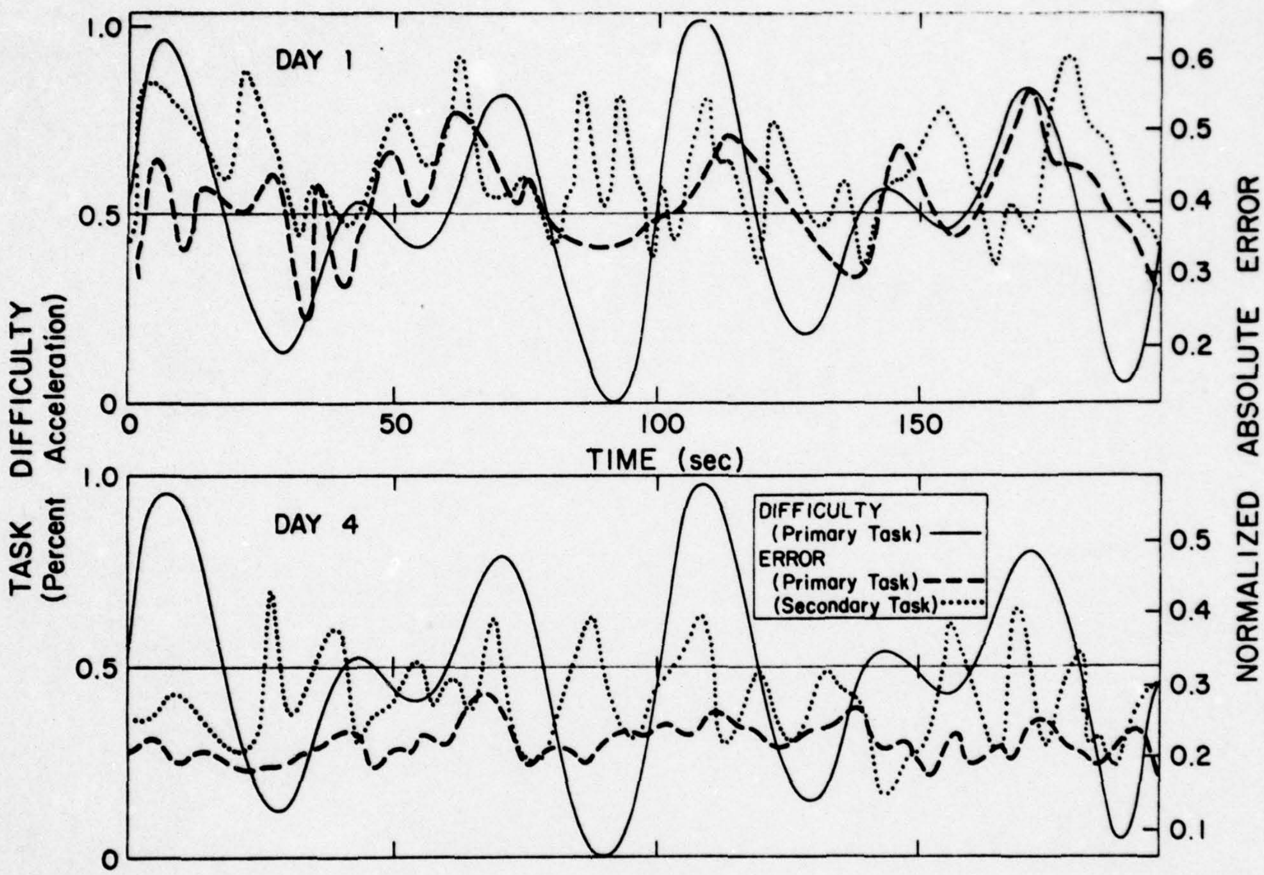

Figure 3: Resource allocation response as a function of practice (day 1 vs. day 4). From Wickens and Tsang, (1979).

values. Subjects may have been attempting to maintain primary performance at a constant level by "holding aside" resources from both tasks during epochs of the easier levels of the primary task, and expending these reserves only when primary demands were maximum. Had subjects been following this strategy, then performance on the secondary task at the points of lowest primary task demands (approximately 90 seconds and 185 seconds into the trial in figure 3) should have been considerably worse (higher error) than the performance if maximum effort was expended. An estimate of the latter performance level was obtained from the dual task condition of constant primary task difficulty with $\alpha = 0$. A comparison of error values between these two (variable and constant difficulty conditions when $d = 0$), failed to reveal worse performance in the variable condition. It was thereby concluded that subjects were in fact exerting maximum resources at all levels of difficulty in the variable condition, and not simply reserving resources when task demands were lessened.

The composite results of the two investigations--non-optimal allocation in Experiment 1 and in the early trials of Experiment 2, and a trend toward optimal expansion, rather than optimal allocation with practice--are interesting. They seem to suggest that the hydraulic conception suggested by Kahneman (1973), and Wickens and Pierce (1978) that portrays attention as a continuously available commodity whose supply and allocation can readily be modulated in closed loop fashion according to temporarily imposed demands, is perhaps incorrect. Galanter (1976) has proposed that many of the molar aspects of operator performance in complex environments are open loop or ballistic in nature. Plans are formulated and carried out in the absence of a great deal of continuous closed loop adjustment. In the present paradigm, if the secondary task coherence measure is used to operationally define the level of closed loop interaction, then the results of the second study are seemingly consistent with Galanter's view, since secondary task coherence values here were quite small.

In the first experiment (Wickens and Pierce), higher coherence values of the secondary task did point to the existence of a greater degree of closed loop involvement. In accounting for the difference between these studies, it is possible to argue that the dramatic changes in difficulty imposed by Wickens and Pierce, (much more abrupt than those of the second study) were sufficiently salient to disrupt the open loop allocation

strategy that subjects might otherwise tend to adopt, and force a discrete, all-or-none reallocation of resources. This behavior would more approximate the kind of reallocation strategy that would characterize demand variations between trials. Task difficulty characteristics are known in advance, and an appropriate allocation strategy is chosen at the outset.

In summary, it is clear that considerably more investigation is needed into the characteristics of operator performance in dynamic conditions in order to understand how conceptualizations of the construct we refer to as attention, formulated on the basis of research in constant task environments, must be modified to account for the dynamic aspects of behavior.

Participatory Mode and The Detection Dynamic System Failures

(Colin Kessel, Christopher Wickens)

Our research interest in this area was instigated by two related concerns: One of these related to the differences in performance between the human operator as an active participant in the control of a dynamic system, and as a passive monitor of that system under automatic control. Recent advances in computer technology have generated an evolution toward systems of the latter category and with this evolution in mind, we hoped to identify and investigate some possible shortcomings or disadvantages of system performances under automatic, as opposed to manual control. These are shortcomings that should be considered by system designers in their decisions concerning whether or not to automate particular functions. One such disadvantage we felt, could reside in a reduction in the monitor's ability to detect failures, or malfunctions in the dynamic system under supervision, as he is removed from the control loop. The second instigating source for our research was a specific conflict in the experimental literature concerning which mode of participation (autopilot monitoring vs. active manual controlling, designated below as AU vs. MA performance) produced better failure detection. In two previous investigations in which the two modes had been compared, Young (1969) provided evidence for better MA detection, while Ephrath and Curry (1977) obtained results indicating the opposite conclusions.

In contrasting analytically the two participatory modes, it is possible to identify on paper, characteristics of each that might enhance failure detection over the other. We have listed and described these characteristics in detail in Wickens and Kessel (1977, 1979a) and in Kessel and Wickens (1978); however the most salient of these will be briefly restated here. It is certainly plausible to assert that detection of system failures might be superior while that system is actively under manual control. The operator in the MA mode is constantly interacting with the system; he receives both visual input concerning system state, as well as proprioceptive input concerning the control commands that he has delivered to the system, the latter unavailable to the AU monitor. Furthermore, unlike the AU monitor, he has the option of introducing "test" signals into a system, suspected to be malfunctioning, and observe the subsequent response. Finally the MA controller

may have contructed a better "internal model" of the system, by virtue of his greater degree of active participation. Thereby he should have more reliable expectations of system outputs to known inputs under normal operating conditions and, as a consequence a greater ability to detect departures from normality.

While these factors all favor MA detection, this superiority may be diminished, or even eliminated altogether by differences in workload favoring AU detection. The MA controller must perform two tasks concurrently, controlling and detecting, and the workload imposed by the controlling function may be sufficient to interfere with the detection/decision making task. The AU monitor naturally has only the latter task to perform, and this difference in concurrent task load could enhance AU detection. A second source of potential AU superiority relates to operator adaptation. To the extent that the MA controller adapts his control response to preserve normal tracking performance after a failure, and yet is unaware of this adaptation (as McDonnell, 1966 and others have noted may occur), there will be less visual evidence of a failure from the display and thus a reduced likelihood of detection. A non-adapting autopilot on the other hand will continue to produce salient visual evidence of a changed system response following the failure.

Our goal was to develop an experimental paradigm that would allow us to compare system failure detection under AU and MA participatory modes, in such a way that the two modes were as similar as possible except for the operator's responsibility for manual control. After extensive pretesting, the paradigm chosen was one in which operators detected step increases in the order of a system that was tracking a two dimensional target visible on a CRT display. This failure approximated the loss of stability augmentation. The system was either controlled by the operator himself via 2 dimensional joystick (MA mode), or by a computer autopilot, that simulated as closely as possible the human operator's control transfer function. Autopilot parameters were further adjusted in value so that AU tracking "performance" (RMS error) was equivalent to MA performance. Failures, which occurred at an average frequency of five per two minute trial were detected with a trigger press.

In our first experiment (Wickens and Kessel, 1977, 1979a), five subjects, well practiced in the detection task performed in the AU and MA mode on alternate trials. Analysis of detection performance, measured

as a joint function of response latency and accuracy[1] indicated that the MA mode was reliably superior. Latency was considerably shorter while there was minimal difference between modes in terms of response accuracy. Three fine grained analysis techniques were then performed on the detection and tracking data in an effort to identify what characteristics of the operator and/or the two modes were responsible for the obtained MA superiority. These techniques involved (1) examining the distribution of detection response latencies, (2) using multiple regression techniques to regress response latency on characteristics of the tracking control signals in the interval between failure and detection, and (3) constructing separate ensemble averages of the control signals for hit and miss trials following the failure.

The composite evidence derived from these three analyses indicated that MA detection benefited from the presence of qualitatively different information available to the decision-maker in the first second or two after the failure. We concluded that this information consisted of proprioceptive cues, generated by the operator's initial adaptive response (change in control behavior) to the changed dynamics.

One potential source of difference between the two modes, whose effect we were unable to examine in the first study, related to differences in the internal model. Since all subjects received training under both MA and AU conditions, it is reasonable to assume that a uniform internal model, or conception of the system was in force in both conditions. A major goal of our second study (Kessel and Wickens, 1978, the PhD dissertation of the first author) was to ensure the presence of a different internal model between AU and MA detection, and this was accomplished by adopting a between-subjects design. If, as hypothesized, MA training allows for a more stable model to develop, then MA superiority should again be demonstrated and in fact, this superiority should be enhanced relative to the previous within subjects design in which AU detection could benefit from a model developed in part under MA training.

The results obtained by Kessel and Wickens supported this prediction as MA superiority was again demonstrated. Moreover in the between subjects design, MA detection was not only of shorter latency, but also of considerably

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1. A variant of signal detection theory was used to assess response accuracy, thereby rewarding performance for failures detected, as well as penalizing for false alarms (detection response made in the absence of a failure).

greater accuracy than AU detection. In the first study, the difference was only evident in detection latency. In fact the overall degree of MA superiority, assessed in terms of a combined speed-accuracy performance index, was five times greater than in the first study, thereby clearly demonstrating the enhanced differences in learning and model development between the two participatory modes.

In order to further validate these differences, a second phase of the experiment included a transfer condition. If the overall MA superiority was in fact related to what was learned (internal model consistency), as well as to the other performance-related differences (e.g. the added proprioceptive information channel), then some benefit in detection should be provided to subjects detecting failures in the AU mode, if they had previously received MA detection training (MA-AU) when compared to a corresponding AU-AU control group. AU detection of the MA-AU group should benefit from better model development during MA training. To create these conditions, following three sessions of training, each training group (AU and MA) transferred to receive 3 further days of failure detection in the AU mode. The results again substantiated this prediction, as positive transfer in the MA-AU transfer group was observed. Information acquired while tracking clearly benefited detection performance while monitoring. Finally in an additional transfer group that was investigated (AU-MA), no positive transfer was observed from AU training to MA transfer.

The fine grained analyses performed on the detection and control data of Wickens and Kessel (1979a) were repeated on the training and transfer data, in order to determine what characteristics of the task were transferred positively from the MA training to the AU detection. Somewhat surprising here was our observation that, in terms of these indices of control and detection performance, the data of the AU transfer group appeared to show much greater similarity to the data of all of the MA groups (from both experiments) than to those of any of the other AU conditions. As stated on page 12, we had previously attributed the differences between the MA and AU groups revealed by the fine grained analyses to the availability of proprioceptive evidence in the MA condition. However, since the AU transfer group showing these same characteristics clearly had no proprioceptive information available, it appeared that our proprioceptive argument required some modification. The tentative conclusion offered in light of the data from the second experiment, is that MA training served to focus attention on particular kinds of displayed visual

information, particularly that related to the perception of higher derivatives of the error and cursor signals. This information--acceleration and change in acceleration--which must be perceived for effective manual control of the system in its failed state, also can serve as a relevant cue indicating the initiation of a system failure. Thus the essence of the transferred information from MA to AU performance (and one probable source of MA superiority) appears to be perceptual, and attributable to the requirements that effective manual control impose on the operator to extract certain kinds of visual information from the display.

By way of general conclusions, the two studies fairly conclusively demonstrated the existence of MA superiority in failure detection, in the context of the paradigm employed. These results thereby suggest that consequent costs may be associated with design innovations which serve to remove the operator from the control loop. Naturally there will often be factors that override these considerations and will require that the operator be placed in the role of an autopilot supervisor/monitor. In this regard the implication of the transfer study is that a major benefit can accrue to system monitors, if they have received a prior period of manual interaction with the system that is to be under supervision.

The Structure of Processing Resources

Christopher Wickens and Colin Kessel

Another major dimension of our research on failure detection related to the effects of two different loading tasks on detection performance. These loading task manipulations were originally incorporated into the experimental design with the intent of shedding further light upon the detection process. However, the data obtained from them, along with related experimental results from other laboratories (e.g., Wickens, Isreal and Donchin, 1977; Wickens and Harris, 1979; North, 1977) and theoretical views proposed by Navon and Gopher (1977; 1979) and Kantowitz and Knight (1976) facilitated the development of a theoretical conception of the structure underlying human information processing resources. While many of the details of this conception are presented in Wickens (1979a) and Wickens and Kessel (1979b), its basic tenants will be outlined below.

The concept that humans possess an underlying "pool" or reservoir of processing capacity that is mobilized in the performance of any task, has proven to be a useful metaphor for accounting for the results of much dual task research (e.g., Moray, 1967; Kahneman, 1973). Furthermore this concept serves as the theoretical framework underlying the application of secondary task methodology to workload measurement (Knowles, 1963; Rolfe, 1971). As one task is imposed upon the operator or as it becomes more difficult, more resources are consumed from the limited pool, fewer are available for concurrent activities, and therefore performance on these concurrent tasks is predicted to decline.

While the concept of processing resources is useful, and has stimulated several interesting theoretical developments (e.g., Kahneman, 1973; Norman and Bobrow, 1975), research has brought to light a number of examples that are at odds with the assertion that all resources reside within a single undifferentiated reservoir, equally available to all tasks. Specifically Wickens (1979a), has identified a number of examples of "difficulty insensitivity"--cases in which changes in the difficulty (demand for processing resources) of one member of a dual task pair fail to produce variation in the performance of the concurrent task. To cite one example of this phenomenon in the failure detection research described in the previous section, we

found that operator's detection performance in the AU participatory mode was affected neither by the introduction of a concurrent loading task (critical instability tracking), nor by changes in its difficulty.

There are of course a number of possible explanations for these findings. Performance on the primary task may be "data limited" (Norman and Bobrow, 1975). That is, its performance level is governed totally by the quality of perceptual or memory data available and therefore is uninfluenced by the availibility of, or competition for processing resources. Alternatively, performance on the concurrent task may be inadequately controlled, so that that task is not really effective in changing the amount of processing resources required. The pattern of a substantial amount of dual task data, summarized by Wickens (1979a) however, suggests the plausibility of a third possible explanation: based upon the observation that task pairs that manifest difficulty insensitivity often appear to be structurally dissimilar, a plausible assumption is that resources, rather than residing in a single undifferentiated reservoir, are compartmentalized into separate pools defined by the separate processing structures.

A possible configuration of these separate resource reservoirs is one in which they are defined by stages of processing (see figure 4). This representation is consistent with some aspects of dual task research, and with a conventional partitioning of the information processing sequence along these lines (e.g., Welford, 1976; Shaffer, 1973). When a task combination shares common resource demands, as in Case I on the left, a tradeoff between performance on one task, and the difficulty of the other should result. Furthermore, such a pair should show a smooth tradeoff between the performance on both tasks (the performance operating characteristic or POC), as the operator voluntarily shifts his allocation of resources from one task to the other (Norman and Bobrow, 1975; Navon and Gopher, 1977). In contrast, in Case II portrayed on the right, when separate, non-overlapping processing structures are demanded by the tasks, difficulty insensitivity will result and the POC will be discontinuous.

A major purpose of the dual task loading manipulations employed in our failure detection research (Wickens and Kessel, 1979b) was to assess whether predictions of task interference patterns, based upon the postulation of separate processing resource pools, would be substantiated when two qualitatively different loading tasks were employed. The critical instability tracking task (Jex, 1967) mentioned above was assumed to place its greatest demand

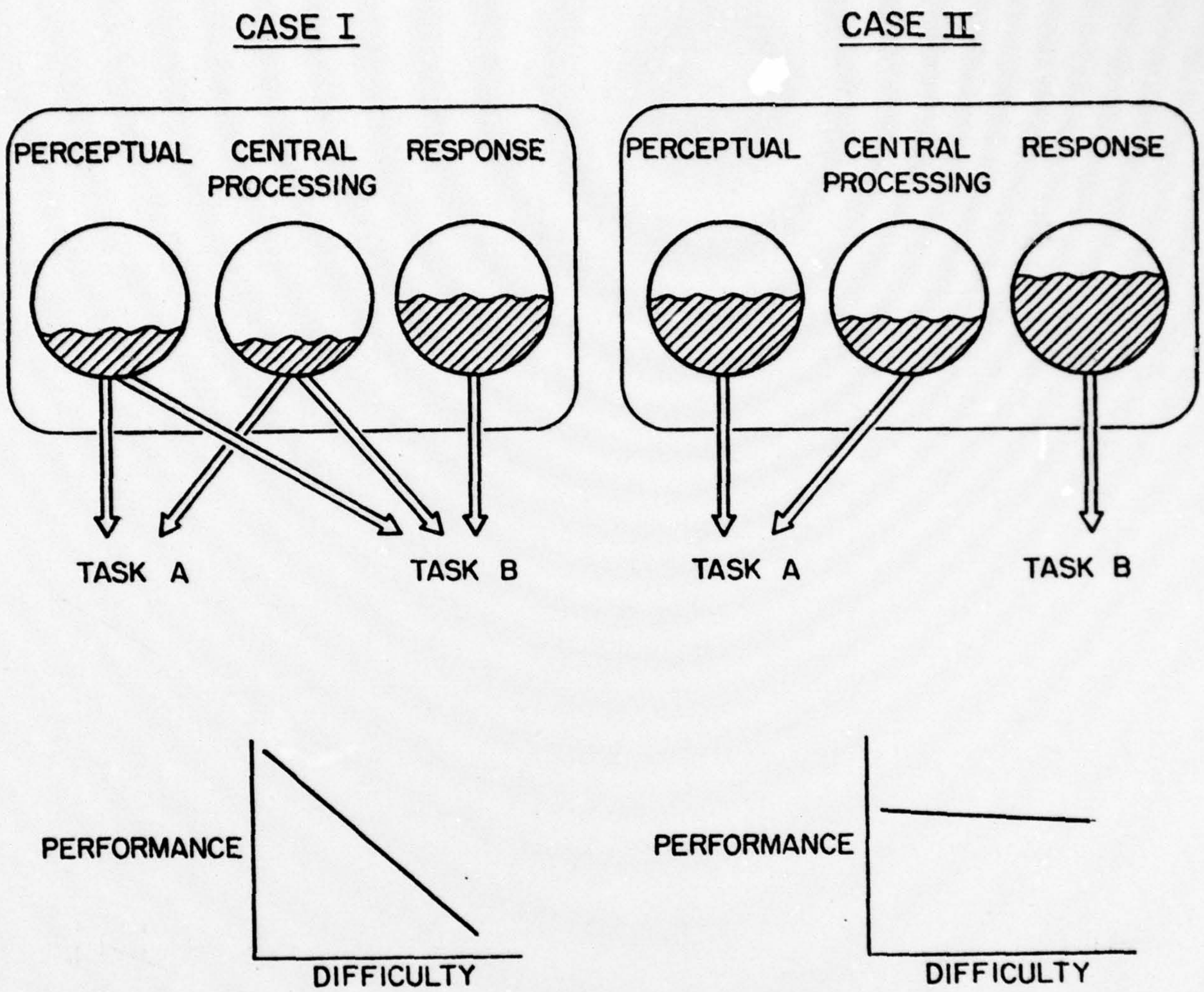

Figure 4: Representation of structure-specific resources predicting difficulty performance tradeoffs.

upon response-related resources, while a running memory mental arithmetic task was assumed to depend heavily upon central processing.

The effects of these two loading tasks were found to be qualitatively different in the two participatory modes. The critical task interfered with detection in the MA mode, but had no effect upon AU detection. Exactly the opposite pattern was observed for the mental arithmetic task which derogated AU detection but influenced neither MA detection nor the operator's tracking performance in the MA mode. If it is assumed, as we concluded from the initial Wickens and Kessel (1977; 1979a) study (see p. 13 above), that detection in the MA mode differed from AU detection in that the former was more dependent upon response-related information, then these dual task results are quite consistent with the multiple reservoir concept. Only one modification of the scheme presented in figure 4 need be made. This modification is a parsimonious one and combines the "encoding" and "central processing" reservoirs depicted into a single reservoir. Then it is assumed that MA detection, relying more upon response-related information will compete with the critical task, but not with mental arithmetic for response resources. AU detection depending exclusively upon visual/perceptual information will compete for resources with mental arithmetic but not with the critical task. If competition for resources implies a dual task decrement, then the results are directly explained.

The results of this dual task research are thus encouraging with regard to the concept of multiple resource reservoirs, and serve to support the theoretical positions adopted by Navon and Gopher, (1977), Kantowitz and Knight (1976) and ourselves (Wickens, 1979b). However, an extensive program of research is certainly required to identify more specifically the demand composition of these reservoirs, and to determine the extent to which they may be defined perhaps by modalities of input or output, or by cerebral hemispheres of processing as well as processing stages. When provided with such information the human factors researcher will thus be equipped with a theoretical framework to make an appropriate selection of secondary tasks for assessing workload differences (Wickens, 1979b), and also for predicting a priori what task combinations will yield maximum or minimum interference when performed concurrently.

REFERENCES

Ephrath, A.R. and Curry, R.E. Detection by pilots of system failures during instrument landings. IEEE Transactions on System Man and Cybernetics, 1977, SMC-7, pp. 841-848.

Galanter, E. Human Performance Capabilities. ONR Final Report, Columbia University, October 1976. AD A031 462.

Jex, H.R. Two applications of the critical instability task to secondary workload research. IEEE Transactions on Human Factors in Electronics. 1967, HFE-8, pp. 279-282.

Kahneman, D. Attention and Effort. Englewood Cliffs, N.J.: Prentice Hall, 1973.

Kantowitz, B.H. and Knight, J.L. Testing tapping timesharing: II. Auditory secondary task. Acta Psychologica, 1976, 40, 343-362.

Keele, S.W. Attention and human performance. California: Goodyear Publishing Company, 1973.

Kerr, B. Processing demands during mental operations. Memory and Cognition, 1973, 1, 401-412.

Kessel, C. and Wickens, C. Development and utilization of internal models in dynamic systems. A comparison of monitors and operators as failure detectors. University of Illinois Engineering-Psychology Laboratory, Technical Report EPL-78-2/AFOSR-78-5, December 1978.

Knowles, W.B. Operator loading tasks. Human Factors, 1963, 5, pp. 151-161.

McDonnell, J.D. A preliminary study of human operator behavior following step changes in the controlled element. IEEE Transactions on Human Factors in Electronics, 1966, HFE-6, p. 125-129.

Moray, N. Where is capacity limited? A survey and a model. Acta Psychologica. 1967, 27, p. 89-92.

Navon, D. and Gopher D. On the economy of the human processing system: A model of multiple capacity. The Technion Israeli Institute of Technology, Technical Report AFOSR-77-1, 1977.

Navon, D. and Gopher, D. Interpretations of task difficulty in terms of resources. In R. Nickerson and R. Pew (Eds.) Attention and Performance VIII. Englewood Cliffs, N.J.: Lawrence Erlbaum, 1979 (in press).

Norman, D. and Bobrow, D.G. On data limited and resource limited processes Journal of Cognitive Psychology, 1975, 7, p. 44-64.

North R.A. Task components and demands as factors in dual-task performance. Savoy, IL: University of Illinois at Urbana-Champaign, Institute of Aviation, Aviation Research Laboratory, Technical Report ARL-77-2/AFOSR-77-2, January 1977.

North R. and Gopher, D. Measures of attention as predictors of flight performance. Human Factors, 1976, 18, p. 1-14.

Rolfe, J. The secondary task as a measure of mental load. In Singleton, Easterby and Whitfield (Eds.). Measurement of man at work. London: Taylor and Francis, 1971.

Shaffer, L.H. Latency mechanisms in transcription. In S. Kornblum (Ed.) Attention and Performance IV, New York: Academic Press, 1973.

Welford, A. Skilled Performance: Glenview, IL: Scott Foresman, 1976.

(a) Wickens, C.D. The structure of attentional resources. In R. Nickerson and R. Pew (Eds.) Attention and Performance VIII, Englewood Cliffs, N.J.: Lawrence Erlbaum, 1979 (in press).

(b) Wickens, C.D. Measures of workload, stress and secondary tasks. In N. Moray (Ed.) Human Workload: Its Theory and Measurement. Plenum press, 1978 (in press), p. 77-99.

Wickens, C.D. and Harris, S. Effects of input and output modalities and task difficulty on time-sharing performance. Naval Aeromedical Research Laboratory, Pensacola, FL, Technical Report (in preparation). (1979).

Wickens, C.D., Isreal, J. and Donchin, E. The event related cortical potential as an index of task workload. Proceedings of the Annual Meeting of the Human Factors Society, San Francisco, CA, 1977.

Wickens, C.D., and Kessel, C. The effect of participatory mode and task workload on the detection of dynamic system failures. Savoy, IL: University of Illinois at Urbana-Champaign, Institute of Aviation, Aviation Research Laboratory, Technical Report ARL-77-8/AFOSR-77-7, June 1977.

(a) Wickens, C.D., and Kessel, C. The effect of participatory mode and task workload on the detection of dynamic system failures. IEEE Transactions on Systems Man and Cybernetics, 1979, SMC-9, #1 (in press).

(b) Wickens, C.D. and Kessel, C. The processing resource demands of failure detection in dynamic systems. University of Illinois Engineering-Psychology Research Laboratory, Technical Report EPL-79-1/AFOSR-79-1. January 1979.

Wickens, C.D. and Peirce, B. Attentional resource allocation in a variable difficulty dual task paradigm. University of Illinois Engineering-Psychology Laboratory Technical Report EPL-78-1/AFOSR-78-1, March, 1978.

Wickens, C.D. and Tsang, P. The dynamics of resource allocation. University of Illinois, Engineering-Psychology Laboratory, Technical Report EPL-78-3/AFOSR-78-3 (in preparation). (1979).

Young, L.R. On adaptive manual control. IEEE Transactions on Man-Machine Systems, V. MMS-10, 1969, 4, p. 292-331.

Scientific Reports Published or in Preparation

Kessel, C. and Wickens, C.D. Development and utilization of internal models in dynamic systems. A comparison of monitors and operators as failure detectors. University of Illinois, Engineering Psychology Laboratory Technical Report EPL-78-2/AFOSR-78-5, December 1978.

Wickens, C.D. The structure of processing resources. In R. Nickerson and R. Pew (Eds.) Attention and Performance VIII. New York: Erlbaum, 1979 (in press.)

Wickens, C.D. and Kessel, C. The effect of participatory mode and task workload on the detection of dynamic system failures. 12th Annual Conference on Manual Control, U.S. Government, 1977. Also Aviation Research Laboratory Technical Report ARL-77-2/AFOSR-77-7, June, 1977.

Wickens, C.D. and Kessel, C. The effect of participatory mode and task workload on the detection of dynamic system failures. IEEE Transactions on System Man and Cybernetics, 1979, 13, No. 1 (in press).

Wickens, C.D. and Kessel, C. The processing resource demands of failure detection in dynamic systems. University of Illinois, Engineering-Psychology Laboratory, Technical Report, EPL-79-1/AFOSR-79-1, January 1979.

Wickens, C.D. and Pierce, B. Attentional resource allocation in a variable difficulty dual task paradigm. Engineering-Psychology Laboratory Technical Report AFOSR-78-1/EPL-78-1, January, 1978.

Wickens, C.D. and Pierce B. Linear modelling of attentional resource allocation. Proceedings, 14th Annual Conference on Manual Control. 1978.

Wickens, C.D. and Tsang, P. Attention allocation in dynamic environments. University of Illinois, Engineering-Psychology Laboratory, Technical Report EPL-79-3/AFOSR-79-3 (in preparation).

Damos, D.L. and Wickens, C.D. The identification and transfer of time-sharing skills. Acta Psychologica (under editorial review).

Earing, R. and Wickens, C.D. Expectancy effects in adapting to abrupt control failures. IEEE Transactions in System Man and Cybernetics (under editorial review).

Presentations at Scientific Meetings

Kessel, C. and Wickens, C. The internal model: The relative contribution of proprioception and vision in failure detection. 14th Annual Conference on Manual Control. University of Southern California, April 1978.

Kessel, C. The development and utilization of internal models of dynamic systems. A comparison of monitoring and controlling. Psychonomics Society Meeting, San Antonio, Texas, November 1978.

Wickens, C. and Pierce, B. Linear modelling of attentional resource allocation. 14th Annual Conference on Manual Control. University of Southern California, April 1978.

Wickens, C.D. Shortcomings of Traditional Workload Assessment Techniques. Airline Pilots Association Symposium on Advances in Workload Study. Washington, D.C. July, 1978.

Wickens, C.D. The structure of processing resources. 8th Symposium on Attention and Performance, Princeton, New Jersey, August 1978.

Wickens, C.D. Human Performance in Time-Varying Environments: Failure detection and attention allocation. Reveiw of Air Force Basic Research in Visual Processes and Human Operator Control. Dayton, Ohio, September 1978.

Wickens, C. and Tsang, P. Attentional resource allocation in dynamic environments. Psychonomics Society, 19th Annual meeting, San Antonio, Texas, November, 1978.

Theses and Dissertations

The following theses and dissertations were based on research supported during the grant period June 1977 - December 1978.

Earing, Robert: The effect of expectancy and training on failure detection performance. Master of Arts in Psychology, December 1977.

Kessel, Colin: Development and utilization of internal models of dynamic systems: A comparison of monitors and operators as failure detectors. Doctor of Philosophy, August 1978.

Pierce, Byron: Resource allocation sensitivity to variations in dual task control dynamics. Master of Arts in Psychology, May 1978.

Tsang, Pamela: The dynamics of human resource allocation. Master of Arts in Psychology to be awarded May, 1979.